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RESEARCH MEMORANDUM

A STUDY OF INJECTION PROCESSES FOR 15-PERCENT FLUORINE - 85-PERCENT OXYGEN AND HEPTANE IN A 200-POUND-THRUST ROCKET ENGINE

By M. F. Heidmann

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
January 15, 1957

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SUMMARY

Characteristic exhaust velocity over a range of mixture ratios and variations in combustion gas velocity with distance from the injector were measured for six different injectors with heptane and a mixture of 15 percent by weight fluorine in liquid oxygen. The tests were made with single-element injectors in a 200-pound-thrust engine having a characteristic length of 50 inches. The injectors provided a systematic variation in injection processes and the gains in characteristic velocity from oxidant atomization, fuel atomization, and mixing were evaluated.

The characteristic velocity with no injector-induced atomization and mixing was about 40 percent of the theoretical value. Atomizing and mixing the propellants increased performance to approximately 92 percent of the theoretical value. The largest portion of this increase was obtained from atomizing the fuel. The results were nearly the same as those obtained previously with oxygen and heptane, indicating that spontaneous ignition has a small effect on the relation between propellant injection and combustion. This similarity applies also to the observed combustion instability characteristics.

INTRODUCTION

Experimental data on the performance of six different injectors with normal heptane and a mixture of 15 percent by weight fluorine in oxygen is presented herein. The tests are a continuation of a study in which the relations between propellant preparation and rocket engine performance are systematically evaluated. In reference 1, heptane and 100-percent oxygen are used as propellants, and 10 single-element injectors are evaluated in a 200-pound-thrust engine. Each of these injectors was chosen to emphasize some part of the injection process such as atomization of fuel only, mixing only, etc. (see ref. 1). The six injectors evaluated and reported herein are identical to six used in the reference 1 study and provide a similar variation in injection processes.

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Performance evaluation included a measure of characteristic exhaust velocity c^* over a range of mixture ratios and the axial velocity of combustion gases as a function of distance from the injector.

The primary reason for adding fluorine to the oxygen was to study the effect of changes in chemical reactivity on rocket-engine combustion. A mixture of 15-percent fluorine in oxygen reacts spontaneously with heptane at room temperature, whereas 100-percent oxygen does not. This difference in reactivity is obtained with no appreciable change in the physical properties of the oxidizer. Comparing the results with and without fluorine should show the independent effect of a change in reactivity on the relation between propellant preparation and rocket-engine performance.

Another reason for the work is to learn more about injection processes with fluorine-oxygen mixtures with hydrocarbons. The addition of fluorine to oxygen is of interest as a means of boosting the performance of oxygen-hydrocarbon engines.

APPARATUS AND PROCEDURE

The apparatus and procedure for this study were the same as those reported in reference 1 with only minor modifications.

Rocket Engine

The rocket engine was designed for a nominal thrust of 200 pounds at a chamber pressure of 300 pounds per square inch. The chamber diameter was 2 inches; the length, 8 inches. A convergent nozzle with a throat diameter of 0.791 inch was used. The characteristic length was about 50 inches with a contraction ratio of 6.4. The injector, uncooled chamber, and uncooled nozzle were separable units. Engine ignition was spontaneous upon contact of the propellants.

Fluorine-Oxygen Mixtures

The installation and use of the oxidant tank were modified from reference 1 as follows. The tank was suspended from a strain-gage-type weight system and weighed while immersed in liquid nitrogen. Next, a prescribed amount of liquid oxygen was loaded into the tank. Gaseous fluorine was then condensed in the tank by bubbling it through the oxygen until weight measurements indicated 15-percent fluorine; the fluorine concentration actually varied between 14 and 16 percent of the total oxidant weight.

The density of the 15-percent mixture at liquid nitrogen temperature (140° R) is 1.248 compared with 1.206 for 100-percent oxygen. This mixture density was calculated using a fluorine density of 1.558 (ref. 2). The boiling points at 1 atmosphere for oxygen and fluorine are 162° and 153° R, respectively.

Injectors

The six injectors shown in figure 1 were investigated. These injectors provided a systematic variation in injection processes. The injectors are the same as those used for the liquid oxygen and heptane studies reported in reference 1.

Performance Measurements

Injector performance was evaluated by determining the characteristic exhaust velocity as a function of mixture ratio and the chamber gas velocity as a function of the distance from the injector at a mixture ratio of about 2.4.

The characteristic exhaust velocity as a function of mixture ratio was obtained from the measurement of chamber pressure, and oxidant- and fuel-flow rates. Chamber pressure was measured at the injector face with both a recording-type Bourdon tube and a strain-gage-type pressure transducer. Flow rates were measured by rotating-vane-type flowmeters. The liquid oxygen was maintained at constant temperature in a liquid-nitrogen bath. Calibrations of the flow and pressure indicators showed an accuracy of approximately ± 1 percent. However, a maximum deviation of ± 5 percent in c^* measurements was obtained experimentally with several injectors.

Combustion-gas velocity as a function of distance from the injector was obtained from streak photographs of the combustion gas flow. The technique used was similar to that described in reference 1 except that sheet-metal liners were placed within the transparent plastic chambers. The liners reduced the erosion and burning of the plastic. Apertures 1/4 inch wide were cut in the liner for the streak photography. Simultaneous streak photographs of the gas flow viewed from two directions 90° apart were obtained in this study, whereas only one view was used in the previous study. Gas velocities were determined with an error of approximately ± 20 feet per second. An average variation in gas velocity with distance from the injector was obtained from approximately ten velocity determinations made at each of seven combustor stations. The data are presented for each view as the percentage of the final velocity observed in the chamber for that view. The final velocities of the two views agreed with each other within experimental error; they were of the order of 150 to 350 feet per second.

Test Procedure

The characteristic exhaust velocity c^* was determined for each injector for oxidant-fuel weight ratios (mixture ratio) from about 1.2 to 4.0. Test firings were of about 3 seconds duration except for several variable-mixture-ratio firings of about 12 seconds duration. The total flow rate was maintained constant at about 0.9 pound per second for most test conditions.

RESULTS AND DISCUSSION

Injector Performance

Characteristic velocity over a range of mixture ratios and chamber gas velocity as a function of distance from the injector are shown for the six injectors in figures 2 to 7. The performance data from the oxygen-heptane study (ref. 1) are included in these figures for a direct comparison of the effect of fluorine addition on performance. Table I is a tabulation of experimental data for the fluorine-oxygen mixtures.

No atomization or mixing. - The c^* efficiency for the parallel-jets injector (fig. 2(a)) was about 40 percent with both 15-percent fluorine and 100-percent oxygen. The incidence of combustion instability was also similar for both propellants. The chamber gas velocity (fig. 2(b)) indicates that combustion is initiated closer to the injector with fluorine. The difference, however, could be partially attributed to different test conditions. (Sheet-metal liners were used in the plastic chambers during the fluorine tests.) Variations in gas velocity as viewed from two directions denotes a large-scale turbulence near the injector.

Oxygen atomization. - The c^* for the oxidant-sheets, fuel-jet injector, (fig. 3(a)) is about the same percentage of theoretical c^* with or without the fluorine addition to the oxygen. No combustion instability was encountered with either propellant. Fluorine added to the oxygen does not alter the chamber gas velocity variations (fig. 3(b)). The presence of large-scale turbulence is again indicated.

Fuel atomization. - The c^* for the fuel-sheet, oxidant-jets injector (fig. 4(a)) at a mixture ratio of 2.5 for peak theoretical c^* was 75.5 percent of theoretical with 15-percent fluorine and 72 percent with 100-percent oxygen. The incidence of combustion instability was less with 15-percent fluorine. The gas velocity (fig. 4(b)) was similar with both propellants. The velocity variations indicate a decrease in large-scale turbulence near the injector compared with the parellel-jets and oxidant-sheets, fuel-jet injectors.

Oxidant and fuel atomization. - The c^* efficiency for the parallel-sheets injector, shown in figure 5(a), was about 82 percent at the mixture ratio for peak theoretical c^* for both propellants. The performance curves appear to deviate in the fuel-rich region although the data for 15-percent fluorine are scattered in this region. The scattering may be due to the intermittent periods of combustion instability that often occurred during test firings. The gas velocity increased linearly with distance from the injector (fig. 5(b)) with no indication of large-scale turbulence. The result is about the same with 100-percent oxygen.

4231 Mixing before atomization. - The c^* efficiency for the impinging-jets injector was 92 percent at the mixture ratio for peak theoretical c^* (fig. 6(a)). Stable operation was not obtained for 100-percent oxygen at this condition, but the extrapolated value was also about 92 percent of theoretical. Better performance in the fuel-rich region was obtained with 15-percent fluorine than with 100-percent oxygen. Combustion instability was prevalent with both oxidants at a mixture ratio greater than 2.0. The c^* during combustion instability was only 1 to 2 percent higher than during stable combustion; the increase was much larger for the previous injectors. The c^* level, however, was similar for all injectors when combustion instability occurred.

The gas velocity (fig. 6(b)) reached a maximum value about 5 inches from the injector. A similar result was obtained with 100-percent oxygen.

Mixing after atomization. - The c^* efficiency at the mixture ratio for peak theoretical c^* for the impinging-sheets injector (fig. 7(a)) was 85 and 87 percent for 15-percent fluorine and 100-percent oxygen, respectively. The scattered data for fluorine may again be due to the high incidence of intermittent combustion instability during test firings. The gas velocity (fig. 7(b)) was nearly identical for the two views. The shape of the curve differs somewhat from that obtained with 100-percent oxygen. Changes in test procedure and experimental accuracy, however, may account for some of this difference.

Evaluation of Injection Processes

The improvements in characteristic exhaust velocity c^* gained from oxidant atomization, fuel atomization, and mixing were evaluated from a comparison of the c^* performance of the six injectors. These evaluations were made from the following six comparisons:

Injection process	Injectors compared
Oxidant atomization:	
(1) Fuel not atomized	Oxidant sheets, fuel jet against parallel jets
(2) Fuel atomized	Fuel sheet, oxidant jets against parallel sheets
Fuel atomization:	
(3) Oxidant not atomized	Fuel sheet, oxidant jets against parallel jets
(4) Oxidant atomized	Oxidant sheets, fuel jet against parallel sheets
Mixing:	
(5) Before atomization	Impinging jets against parallel sheets
(6) After atomization	Impinging sheets against parallel sheets

The c^* efficiency of each of these pairs of injectors is shown in figure 8 where results for both 15-percent fluorine and 100-percent oxygen are compared in a parallel arrangement. The shaded area between the two curves represents the gain in performance obtained from the injection processes.

Some of the comparisons in figure 8 show that the gain in c^* depends on mixture ratio. This gain in c^* may be due to variation in injection conditions. For example, the pressure drop across the fuel orifices decreases with an increase in mixture ratio. The fuel atomization therefore is expected to be better at low mixture ratios. Similar variations with mixture ratio occur with oxidant atomization and mixing.

The improvements in c^* performance at a mixture ratio of 2.5 for the injection processes can be compared with the results of references 1 and 3. The c^* efficiency increments of figure 8 and the data of reference 3 were divided by the difference between theoretical c^* and c^* for the parallel-jets injector. The factor obtained provides a means of comparing the effects of injection processes among all three propellants. The comparison factors for the propellants investigated are summarized in the following table:

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Injection process	15-Percent fluorine, 85-percent oxygen, and heptane	Oxygen and heptane	Oxygen and hydrogen
Oxidant atomization:			
(1) Fuel not atomized	17	15	55
(2) Fuel atomized	9	18	11
Fuel atomization:			
(3) Oxidant not atomized	59	53	66
(4) Oxidant atomized	51	55	23
Mixing:			
(5) Before atomization	18	16	0
(6) After atomization	8	9	9

This comparison shows that for 15-percent fluorine the improvement in c^* performance from fuel atomization is about 3.5 times greater than that from oxidant atomization when the other propellant is not atomized (items (3) and (1)) and about 5.5 when the other propellant is atomized (items (4) and (2)). The c^* improvement from fuel atomization is also substantially greater than from mixing although the effect of mixing may increase with shorter chamber lengths as evidenced by the gas velocity measurements. The result indicates that atomizing the less volatile propellant, in this case the heptane, gives the larger c^* performance improvement. These results are similar to those obtained with heptane and oxygen.

The relative effects of the several injection processes were different with gaseous hydrogen and liquid oxygen. For the two conditions when the other propellant was not atomized (items (3) and (1)) and atomized (items (4) and (2)) the gain from hydrogen atomization (dispersion) was only 1.2 and 2.1 times greater than from oxygen atomization. In this case, oxygen would be considered less volatile, and the importance of oxygen atomization relative to fuel atomization increased from that obtained with heptane and oxygen.

Effect of Reactivity on Performance

A comparison of the 15-percent fluorine and 100-percent oxygen results show the effect of spontaneous ignition on the relation between propellant injection and rocket-engine performance. Qualitatively, the effect is small. Both the c^* efficiency and the gains in performance from the various injection processes were similar. For oxidant atomization with atomized fuel (item (2)), the gain in c^* appears larger with 100-percent oxygen than with 15-percent fluorine. It is possible that oxidant atomization is less important with a highly reacting oxidant when the fuel is adequately prepared. However, these small gains in performance (about 10 percent) approach experimental accuracy. In general, it is concluded that spontaneous ignition of propellants does not significantly influence the relation between propellant injection and engine performance.

The results with 15-percent fluorine emphasize the controlling influence of physical processes, such as propellant vaporization and mass diffusion or mixing, on the combustion rate process. These physical processes were appreciably different in the gaseous hydrogen and liquid oxygen study, (ref. 3) and generally higher c^* efficiency and a decreased importance of fuel atomization were observed. Although a change in reactivity was also present with these propellants, the effect of reactivity seems less important in view of the results obtained with 15-percent fluorine. On the basis of such an interpretation, the combustion efficiency of any fuel with fluorine would not be greatly different from the same fuel with oxygen, because the properties of these two oxidizers, which control the physical processes, are nearly the same. Physical processes, however, may not always be controlling. It has been shown (ref. 4) that the decomposition rate of nitric oxide correlates with the over-all combustion rate of jet fuel and nitric acid. Such chemical kinetic processes may be important with other oxidizers as well.

The qualitative results obtained thus far with oxygen and fluorine indicate greater dependence of the combustion process with variations in physical processes than with variations in chemical kinetics. A more thorough investigation of these physical processes, therefore, is suggested. Several factors of both fundamental and practical interest which effect these physical processes are the degree of propellant atomization, propellant vapor pressure, heat of vaporization, and the degree and scale of chamber turbulence. A study of the effect of these factors on rocket-engine performance would lead to a more quantitative evaluation of the combustion-rate process. If variations in chemical kinetics are relatively noncontrolling, as was indicated, such an evaluation of physical processes would provide a qualitative basis for predicting the combustion rate and injector requirements for a given propellant combination.

SUMMARY OF RESULTS

Six injectors which systematically varied injection processes of atomization and mixing were investigated in a 200-pound-thrust rocket engine. Propellants were heptane and a mixture of 15-percent fluorine in liquid oxygen. Characteristic-exhaust-velocity and chamber-gas-velocity measurements were made.

The results of this investigation are summarized as follows:

(1) The characteristic exhaust velocity was about 40 percent of the theoretical value with no atomization and mixing and increased to 92 percent when the propellants were both atomized and mixed.

(2) The gain in characteristic exhaust velocity obtained from fuel atomization was from 3.5 to 5.5 times larger than that obtained from either oxygen atomization or mixing.

(3) The efficiency level and the gains in characteristic exhaust velocity obtained from various injection processes were qualitatively the same as for oxygen and heptane. The similarity indicates that spontaneous propellant ignition does not significantly affect the relation between propellant injection and engine performance.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 12, 1956

REFERENCES

1. Heidmann, M. F., and Auble, C. M.: Injection Principles from Combustion Studies in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane. NACA RM E55C22, 1955.

2. Jarry, Roger L., and Miller, Henry C.: The Density of Liquid Fluorine between 67 and 103° K. Tech. Note OSR-TN-55-286, Whitemarsh Res. Labs., The Pennsylvania Salt Mfg. Co., Nov. 4, 1955. (Contract AFRDC 18(600)761.)

3. Auble, Carmon M.: A Study of Injection Processes for Liquid Oxygen and Gaseous Hydrogen in a 200-Pound-Thrust Rocket Engine. NACA RM E56I25a, 1956.

4. Trent, C. H.: A Study of Combustion of WFNA and JP-3 in Rocket Thrust Chambers. Rep. No. 628, Aerojet Eng. Corp., Nov. 15, 1952. (Contract AF33(038)-2733, Item 30, Proj. MX-1079.)

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TABLE I. - PERFORMANCE DATA

Run	Tank to chamber pressure drop, lb/sq in.		Chamber pressure, lb/sq in. abs.	Oxidant weight flow, lb/sec	Fuel weight flow, lb/sec	Total weight flow, lb/sec	Oxidant-fuel weight ratio	Characteristic exhaust velocity, ft/sec
	Oxidant	Fuel						
Parallel-jets injector								
1	215	210	170	0.749	0.278	1.027	2.67	2600
1	122	117	263	.548	.204	.752	2.69	[a]5500
2	181	206	154	.714	.306	1.020	2.34	2370
3	153	98	152	.651	.182	.833	3.58	2870
4	168	113	157	.675	.210	.885	3.22	2780
5	125	225	130	.565	.324	.889	1.74	2290
6	165	145	150	.685	.241	.926	2.84	2540
Oxidant-sheets, fuel-jet injector								
124	97	67	183	0.705	0.113	0.818	6.23	3520
125	97	67	188	.686	.213	.899	3.22	3280
126	91	101	184	.680	.247	.927	2.75	3120
127	94	129	181	.645	.381	.926	2.30	3080
128	73	152	173	.594	.325	.919	1.83	2960
129	61	206	164	.491	.396	.807	1.24	2900
130	99	79	191	.699	.198	.897	3.53	3340
Fuel-sheet, oxidant-jets injector								
8	133	183	232	0.610	0.202	0.812	3.02	4490
9	121	236	239	.595	.237	.832	2.51	4570
10	112	292	233	.535	.270	.805	1.98	4550
11	92	357	223	.481	.304	.785	1.58	4460
12	175	150	250	.709	.178	.887	3.98	4430
13	160	185	255	.671	.205	.876	3.28	4570
14	128	193	282	.572	.204	.776	2.80	[a]5710
Parallel-sheets injector								
24	138	138	277	0.660	0.195	0.855	3.38	5090
25	115	195	270	.610	.258	.868	2.36	4890
25	115	195	284	.555	.243	.798	2.28	[a]5540
26	165	115	290	.770	.174	.944	4.42	4830
39	98	183	262	.602	.234	.836	2.57	4920
39	98	183	260	.596	.230	.826	2.59	4950
41	91	311	269	.586	.331	.917	1.77	4610
42	87	357	253	.561	.360	.921	1.56	4320
42	87	357	256	.469	.359	.828	1.28	[a]4850
43	120	180	285	.656	.232	.888	2.82	5040
43	120	180	287	.590	.229	.819	2.58	[a]5510
80	106	221	299	.623	.265	.938	2.54	5010
81	116	176	289	.695	.224	.919	3.10	4940
82	109	144	286	.702	.196	.898	3.58	5000
83	109	199	286	.642	.251	.893	2.55	5030

[a]Combustion instability.

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TABLE I. - Continued. PERFORMANCE DATA

Run	Tank to chamber pressure drop, lb/sq in.		Chamber pressure, lb/sq. in. abs.	Oxidant weight flow, lb/sec	Fuel weight flow, lb/sec	Total weight flow, lb/sec	Oxidant-fuel weight ratio	Characteristic exhaust velocity, ft/sec
	Oxidant	Fuel						
Parallel-sheets injector								
83	109	199	295	0.598	0.242	0.840	2.47	[a]5520
98			277	.690	.175	.865	3.94	[a]5330
99			276	.679	.321	1.000	2.11	4580
100			262	.607	.358	.965	1.70	4510
101			199	.492	.383	.875	1.28	3280
102			223	.526	.379	.905	1.39	4100
103			281	.594	.257	.851	2.31	[a]5480
241	108	328	277	.580	.404	.984	1.43	[a]4430
241	108	328	293	.522	.370	.892	1.41	[a]5160
242	97	347	268	.557	.396	.953	1.40	4480
[b]250			297	.672	.208	.870	3.23	[a]5370
			306	.655	.224	.879	2.92	[a]5470
			307	.640	.239	.879	2.68	[a]5500
			311	.623	.256	.883	2.45	[a]5530
			311	.616	.265	.881	2.32	[a]5550
[b]250			314	.600	.284	.884	2.11	[a]5580
			313	.595	.295	.890	2.02	[a]5520
			310	.585	.308	.893	1.90	[a]5450
			309	.572	.323	.895	1.77	[a]5420
			308	.561	.335	.901	1.69	[a]5360
[b]251			305	.559	.342	.901	1.63	[a]5320
			302	.552	.360	.912	1.53	[a]5200
			299	.539	.365	.904	1.48	[a]5200
			297	.533	.374	.907	1.42	[a]5150
[b]251			231	.514	.423	.937	1.21	3880
[b]251			250	.545	.406	.951	1.34	4140
			255	.535	.420	.950	1.27	4220
			263	.537	.393	.930	1.37	4450
			266	.545	.397	.942	1.37	4440
			268	.555	.370	.945	1.42	4460
[b]251			273	.563	.393	.956	1.43	4490
			273	.568	.384	.952	1.48	4500
			276	.584	.375	.959	1.56	4520
			278	.590	.370	.960	1.59	4550
			281	.591	.354	.945	1.67	4670

[a]Combustion instability.
[b]Variable mixture ratio.

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TABLE I. - Continued. PERFORMANCE DATA

Run	Tank to chamber pressure drop, lb/sq in.		Chamber pressure, lb/sq in. abs.	Oxidant weight flow, lb/sec	Fuel weight flow, lb/sec	Total weight flow, lb/sec	Oxidant-fuel weight ratio	Characteristic exhaust velocity, ft/sec
	Oxidant	Fuel						
Parallel-sheets injector								
[b]251			281	0.600	0.351	0.951	1.71	4650
			284	.600	.345	.945	1.74	4720
			284	.615	.333	.948	1.85	4700
			284	.620	.317	.937	1.95	4760
			284	.625	.307	.932	2.04	4780
[b]251			286	.635	.296	.931	2.14	4850
			286	.633	.287	.920	2.20	4880
[b]252			259	.568	.351	.919	1.62	4430
			274	.617	.341	.958	1.81	4490
			277	.611	.332	.943	1.84	4620
[b]252			277	.611	.332	.943	1.84	4620
			277	.617	.334	.951	1.85	4580
			279	.625	.323	.948	1.93	4620
			281	.638	.313	.951	2.04	4650
			282	.643	.304	.947	2.12	4680
[b]252			283	.645	.293	.938	2.20	4740
			283	.650	.278	.928	2.34	4790
			284	.653	.273	.926	2.40	4820
Impinging-jets injector								
17	79	86	211	0.468	0.134	0.602	3.49	5500
18	69	89	236	.491	.165	.656	2.98	5650
18	66	86	239	.496	.158	.654	3.14	[a]5740
19	89	79	256	.587	.154	.741	3.81	[a]5430
19	85	75	260	.607	.155	.762	3.91	5360
19	81	71	259	.601	.149	.750	4.03	[a]5420
20	64	74	231	.512	.150	.662	3.40	5570
20	67	77	228	.488	.148	.636	3.30	5630
20	65	75	230	.495	.144	.639	3.43	[a]5660
21	122	212	223	.446	.340	.786	1.31	4460
21	75	165	270	.530	.280	.810	1.89	5250
28	187	272	203	.375	.391	.766	.96	4170
28	95	180	295	.557	.290	.847	1.92	[a]5470
29	144	289	236	.434	.399	.833	1.09	4450
29	93	238	287	.547	.346	.893	1.58	[a]5050

[a]Combustion instability.
[b]Variable mixture ratio.

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TABLE I. - Continued. PERFORMANCE DATA

Run	Tank to chamber pressure drop, lb/sq in.		Chamber pressure, lb/sq in. abs.	Oxidant weight flow, lb/sec	Fuel weight flow, lb/sec	Total weight flow, lb/sec	Oxidant-fuel weight ratio	Characteristic exhaust velocity, ft/sec
	Oxidant	Fuel						
Impinging-jets injector								
30	103	173	317	0.608	0.281	0.889	2.16	[a]5600
31	121	121	324	.683	.206	.889	3.14	[a]5720
92	101	176	324	.659	.291	.950	2.26	5500
93	101	156	329	.680	.263	.943	2.58	5620
94	104	144	331	.683	.253	.936	2.70	[a]5700
95	107	132	333	.718	.230	.948	3.12	5660
96	112	127	333	.730	.228	.958	3.20	5600
Impinging-sheets injector								
64	131	111	294	0.716	0.163	0.879	4.40	5250
65	102	147	288	.646	.206	.852	3.14	5310
66	98	238	307	.610	.279	.889	2.20	[a]5440
67	67	272	254	.485	.310	.795	1.56	5010
68	56	366	219	.386	.372	.758	1.04	4540
69	105	195	310	.610	.245	.855	2.49	[a]5700
70	125	130	305	.710	.185	.895	3.84	[a]5360
71	62	357	243	.464	.368	.832	1.26	4680
72	97	297	298	.601	.322	.923	1.87	5070
73	105	220	310	.623	.261	.884	2.38	[a]5510
73	110	225	305	.659	.270	.929	2.44	5160
74	115		305	.646	.201	.847	3.22	[a]5650
74	132		288	.694	.216	.910	3.21	4970
75			303	.667	.188	.855	3.54	[a]5570
75			290	.716	.207	.923	3.46	4940
76			309	.619	.234	.853	2.64	[a]5690
76			297	.655	.246	.901	2.61	5160
105	82	257	293	.602	.324	.926	1.86	[a]5410
105	85	260	290	.610	.327	.937	1.87	[a]5300
106	85	220	295	.622	.292	.914	2.13	[a]5510
106	90	225	290	.631	.294	.925	2.14	[a]5350
107	90	185	295	.636	.267	.903	2.38	[a]5590
107	105	200	280	.668	.277	.945	2.41	5070
108	111	161	279	.723	.242	.965	2.98	4950
109	106	151	282	.645	.211	.856	3.05	[a]5650
109	116	161	270	.673	.234	.907	2.88	5100
110	110	120	275	.641	.185	.826	3.46	[a]5650
110	121	131	264	.705	.212	.917	3.32	4930
[b]265			318	.707	.186	.893	3.80	[a]5590
			319	.700	.191	.891	3.67	[a]5620

[a]Combustion instability.
[b]Variable mixture ratio.

[redacted]

TABLE I. - Concluded. PERFORMANCE DATA

Run	Tank to chamber pressure drop, lb/sq in.		Chamber pressure, lb/sq in. abs.	Oxidant weight flow, lb/sec	Fuel weight flow, lb/sec	Total weight flow, lb/sec	Oxidant-fuel weight ratio	Characteristic exhaust velocity, ft/sec
	Oxidant	Fuel						
Impinging-sheets injector								
[b]265			322	0.699	0.203	0.902	3.44	[a]5600
			325	.687	.2175	.9045	3.16	[a]5650
			326	.679	.229	.908	2.96	[a]5640
			327	.665	.239	.904	2.78	[a]5680
			319	.698	.261	.959	2.67	5230
[b]265			320	.690	.264	.954	2.61	5260
			320	.706	.274	.976	2.56	5150
			318	.670	.281	.951	2.38	[a]5250
			326	.628	.286	.910	2.22	[a]5650
			324	.621	.290	.911	2.14	[a]5580
[b]265			322	.615	.298	.913	2.06	[a]5530
			319	.610	.306	.916	1.99	[a]5470
			318	.600	.316	.916	1.90	[a]5450
			315	.587	.329	.916	1.78	[a]5400
			313	.576	.334	.910	1.73	[a]5406
[b]265			309	.568	.346	.914	1.66	[a]5310
			294	.585	.356	.941	1.65	4900
[b]266			303	.565	.346	.911	1.63	[a]5220
			304	.565	.346	.911	1.63	[a]5230
			297	.603	.352	.955	1.71	4890
[b]266			311	.570	.334	.904	1.71	[a]5400
			315	.579	.328	.907	1.76	[a]5450
			317	.585	.324	.909	1.80	[a]5480
			317	.587	.313	.900	1.87	[a]5530
			318	.595	.312	.907	1.90	[a]5500
[b]266			308	.635	.309	.944	2.06	5120
			320	.615	.294	.909	2.09	[a]5530
			321	.618	.291	.909	2.12	[a]5550
			320	.620	.281	.901	2.20	[a]5570
			321	.625	.277	.902	2.26	[a]5590
[b]266			321	.633	.271	.904	2.34	[a]5580
			308	.670	.275	.945	2.44	5120
			322	.633	.261	.894	2.43	[a]5650
			303	.661	.266	.927	2.48	5240
			303	.651	.260	.911	2.50	5320
			318	.635	.240	.875	2.64	[a]5710

[a]Combustion instability.
[b]Variable mixture ratio.

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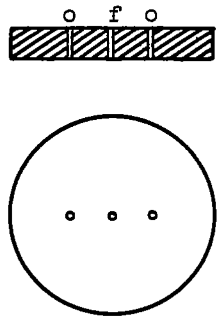
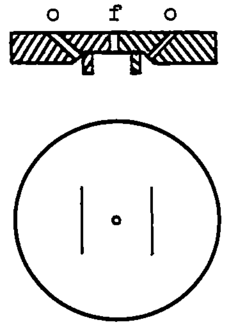
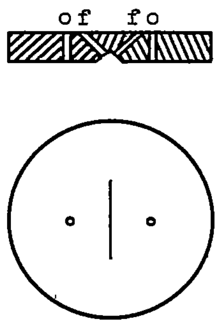


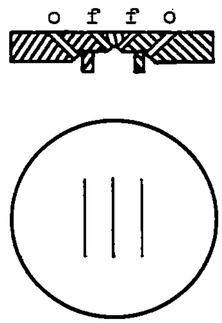
(a) Parallel jets; no atomization or mixing.



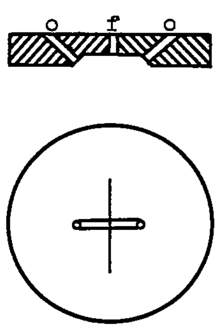
(b) Oxidant sheets, fuel jet; oxidant atomization without mixing.



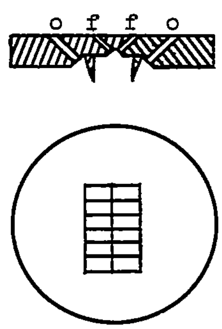
(c) Fuel sheet, oxidant jets; fuel atomization without mixing.



(d) Parallel sheets; oxidant and fuel atomization without mixing.

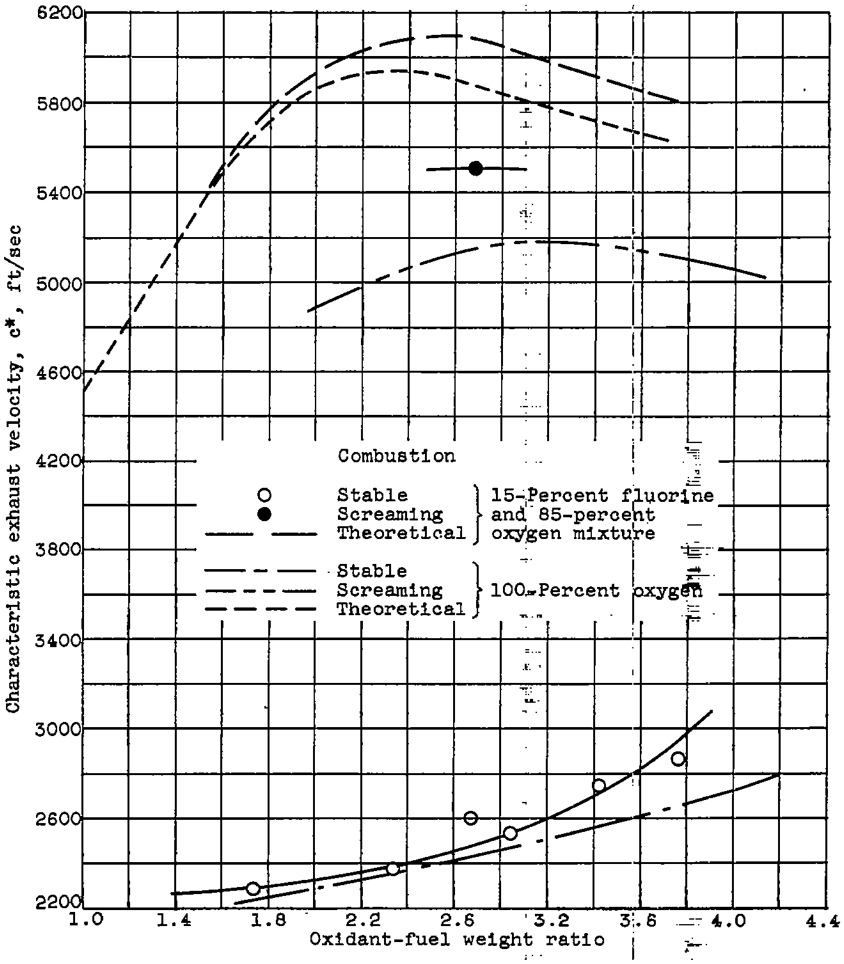


(e) Impinging jets; mixing before atomization.

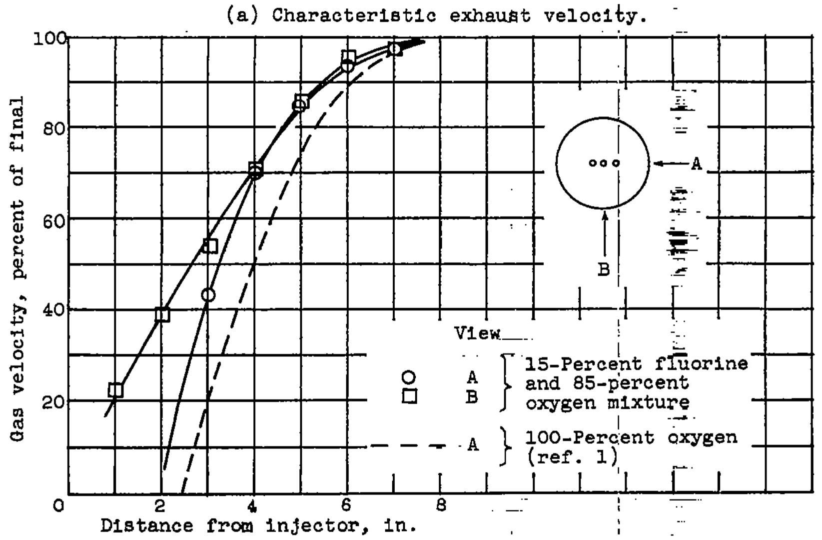


(f) Impinging sheets; mixing after atomization.

Figure 1. - Injector designs and spray patterns. Fuel injection equally spaced between two positions of oxidant injection. Centerline spacing between fuel and oxidant injection, 0.25 inch. Oxidant orifice diameter, 0.111 inch; single fuel orifice diameter, 0.116 inch; double fuel orifice diameter, 0.082 inch.



(a) Characteristic exhaust velocity.



(b) Chamber gas velocity.

Figure 2. - Performance of parallel-jets injector.

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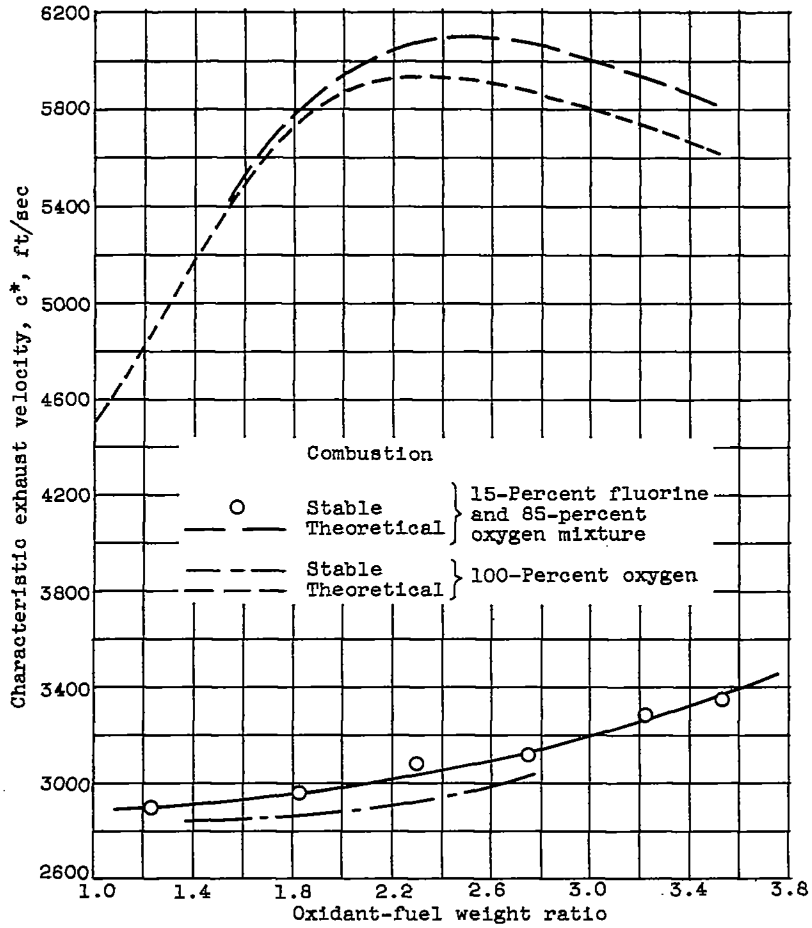
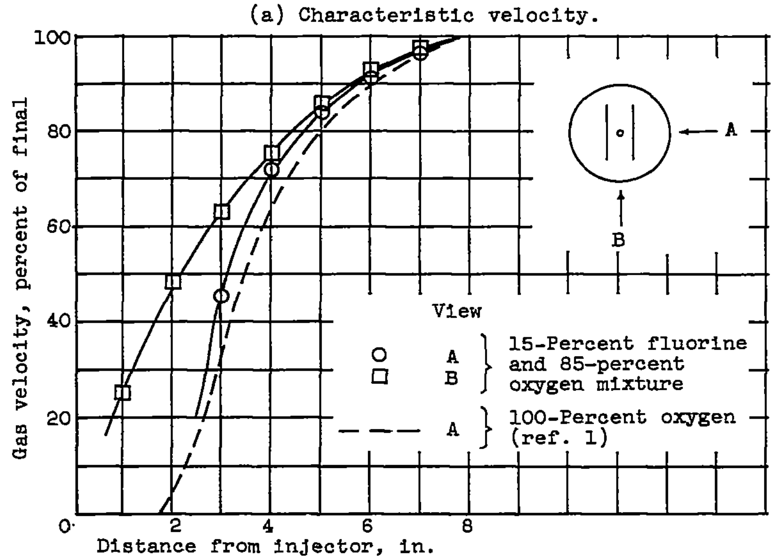
CM-3



(a) Characteristic velocity.



(b) Chamber gas velocity.

Figure 3. - Performance of oxidant-sheets, fuel-jet injector.

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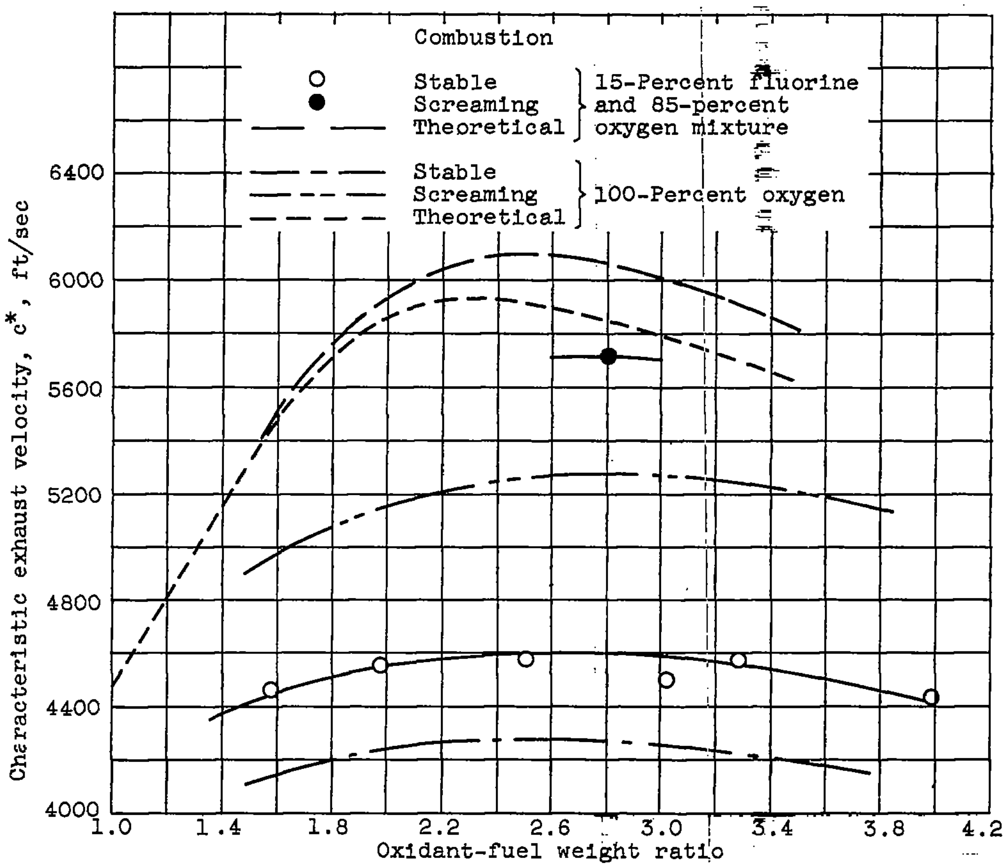
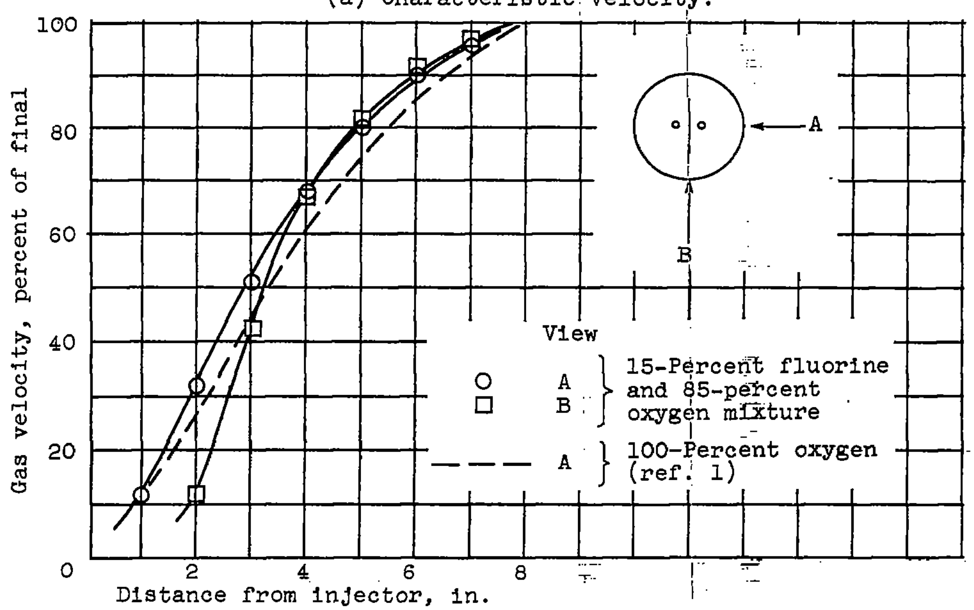


(a) Characteristic velocity.



(b) Chamber gas velocity.

Figure 4. - Performance of fuel-sheet, oxidant-jets injector.

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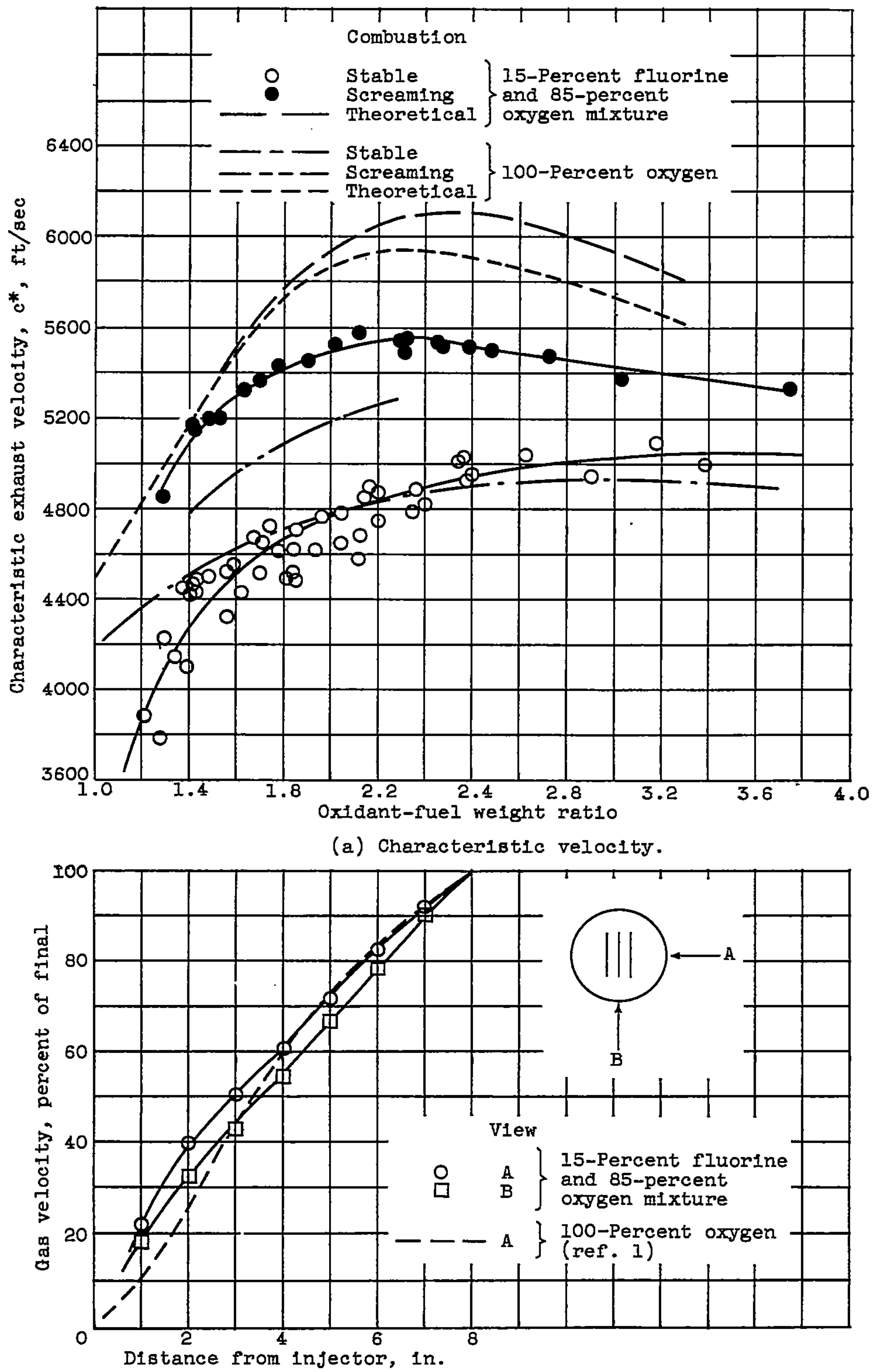
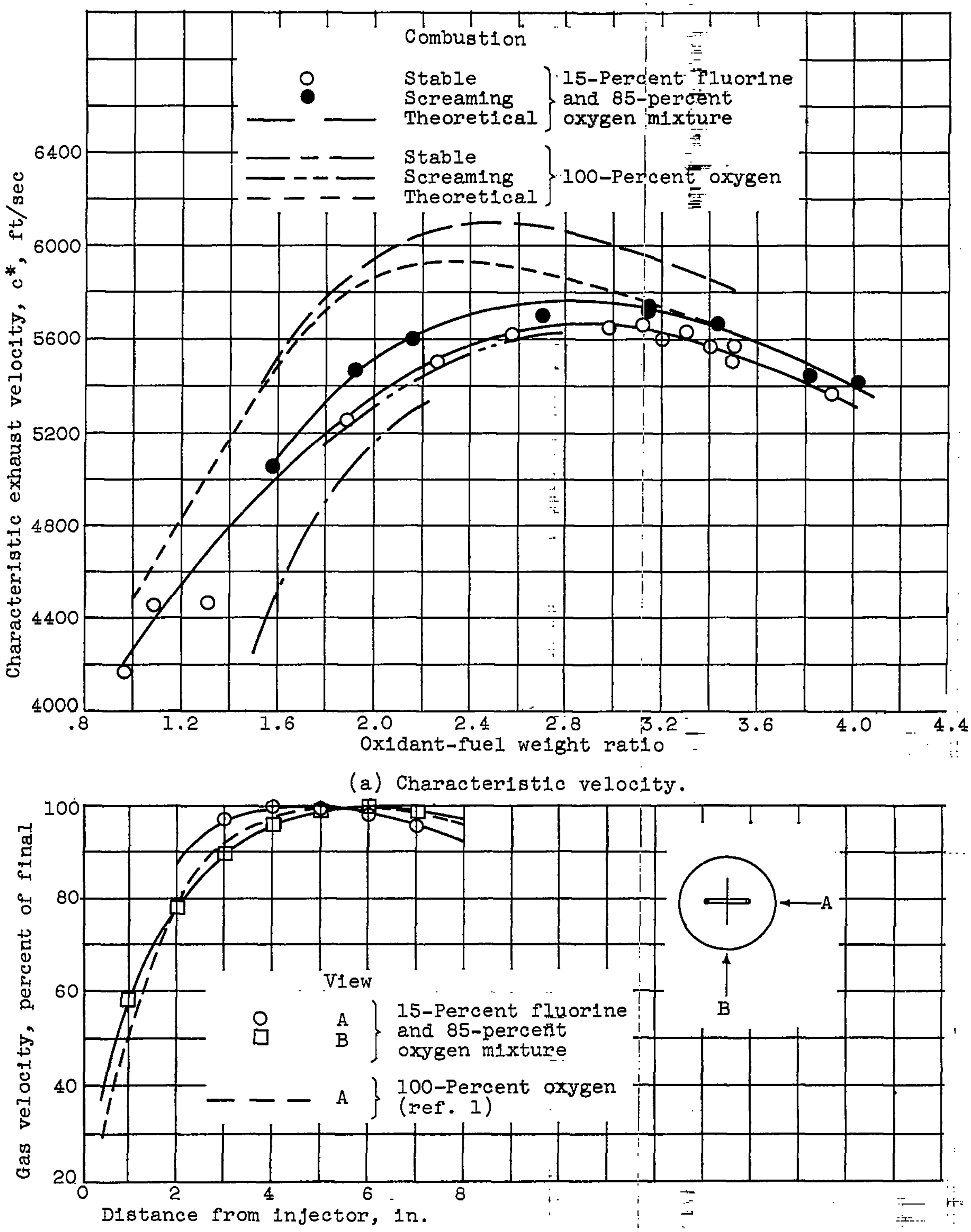
CM-3 back



(a) Characteristic velocity.

(b) Chamber gas velocity.

Figure 5. - Performance of parallel-sheets injector.



(a) Characteristic velocity.

(b) Chamber gas velocity.

Figure 6. - Performance of impinging-jets injector.

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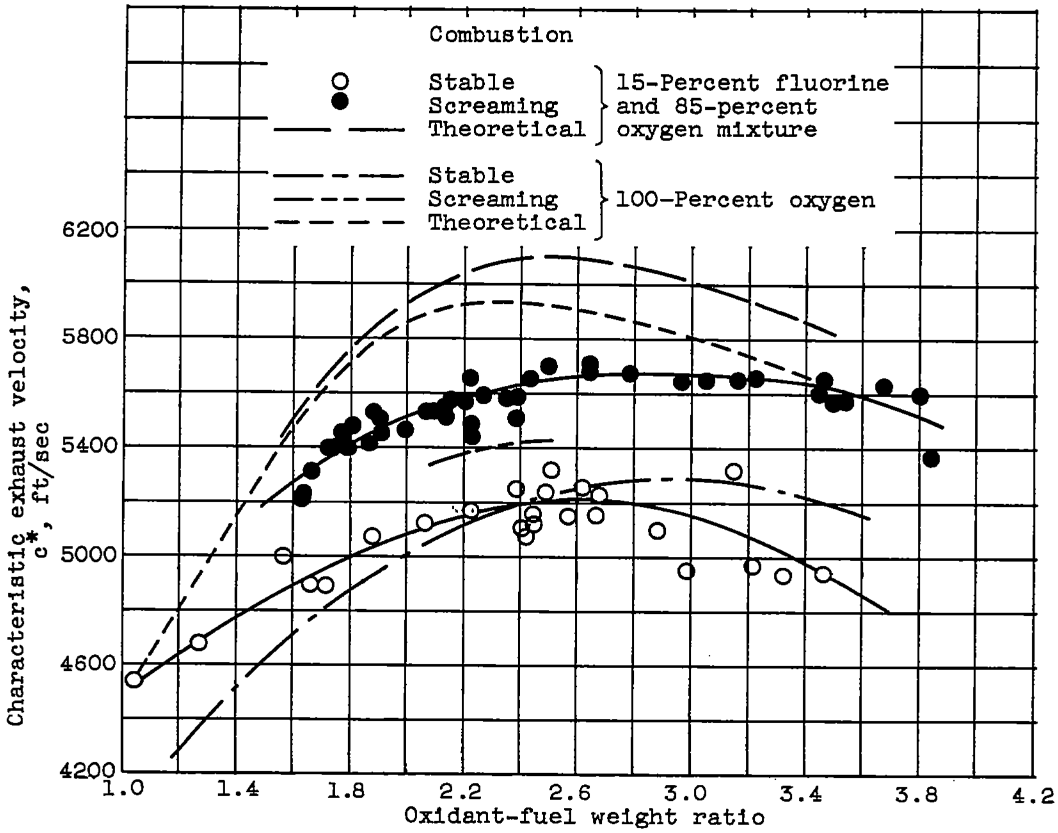
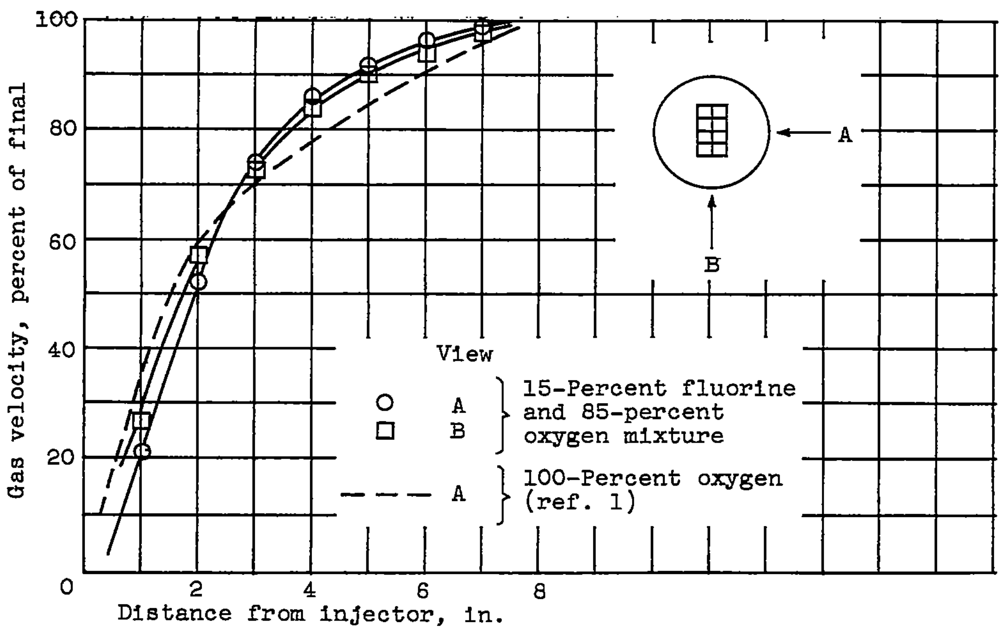


(a) Characteristic velocity.



(b) Chamber gas velocity.

Figure 7. - Performance of impinging-sheets injector.

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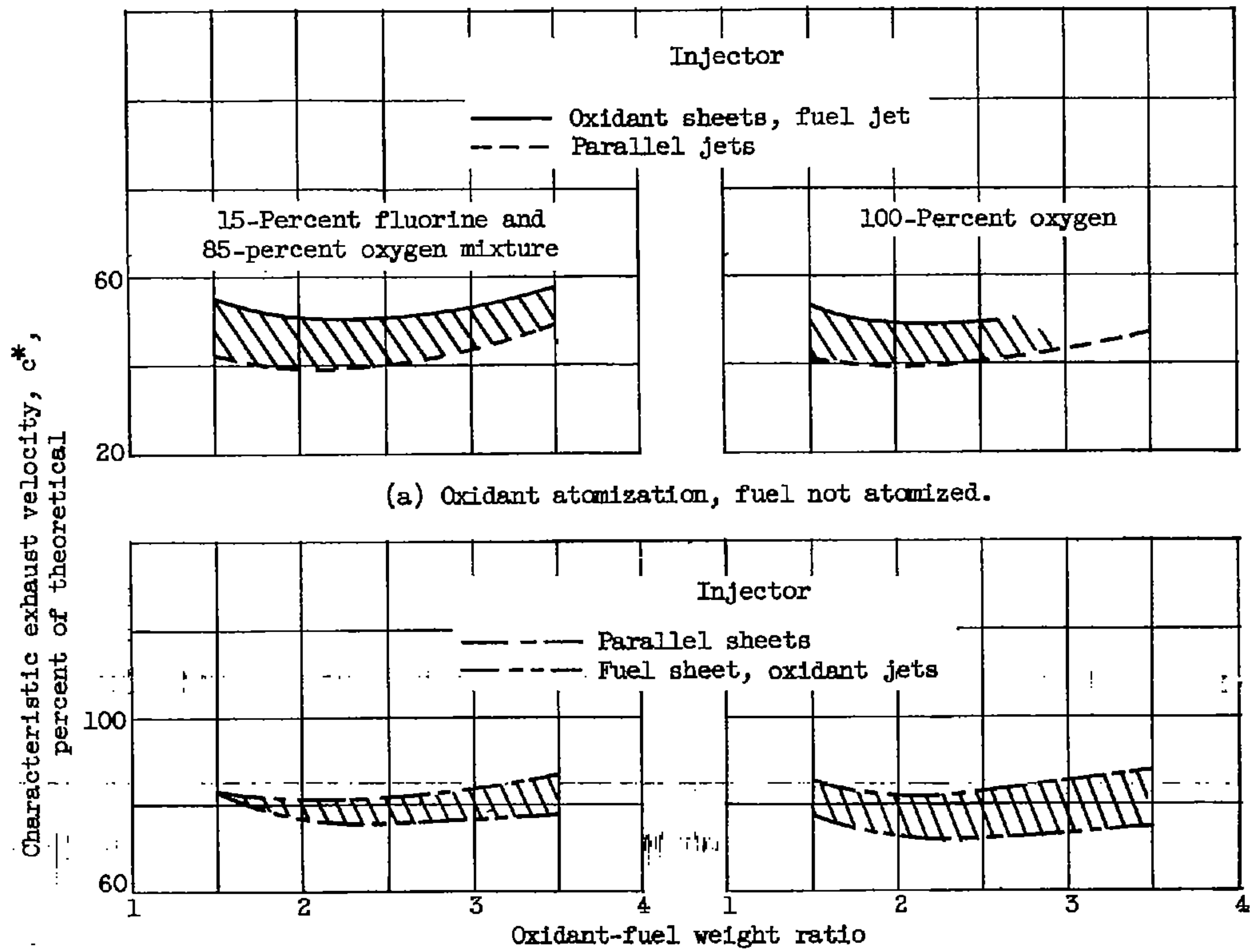

(a) Oxidant atomization, fuel not atomized.

(b) Oxidant atomization, fuel atomized.

Figure 8. - Performance gain for various injection processes from a comparison of injector performance for both 15-percent fluorine and 85-percent oxygen mixture and 100-percent oxygen with heptane.

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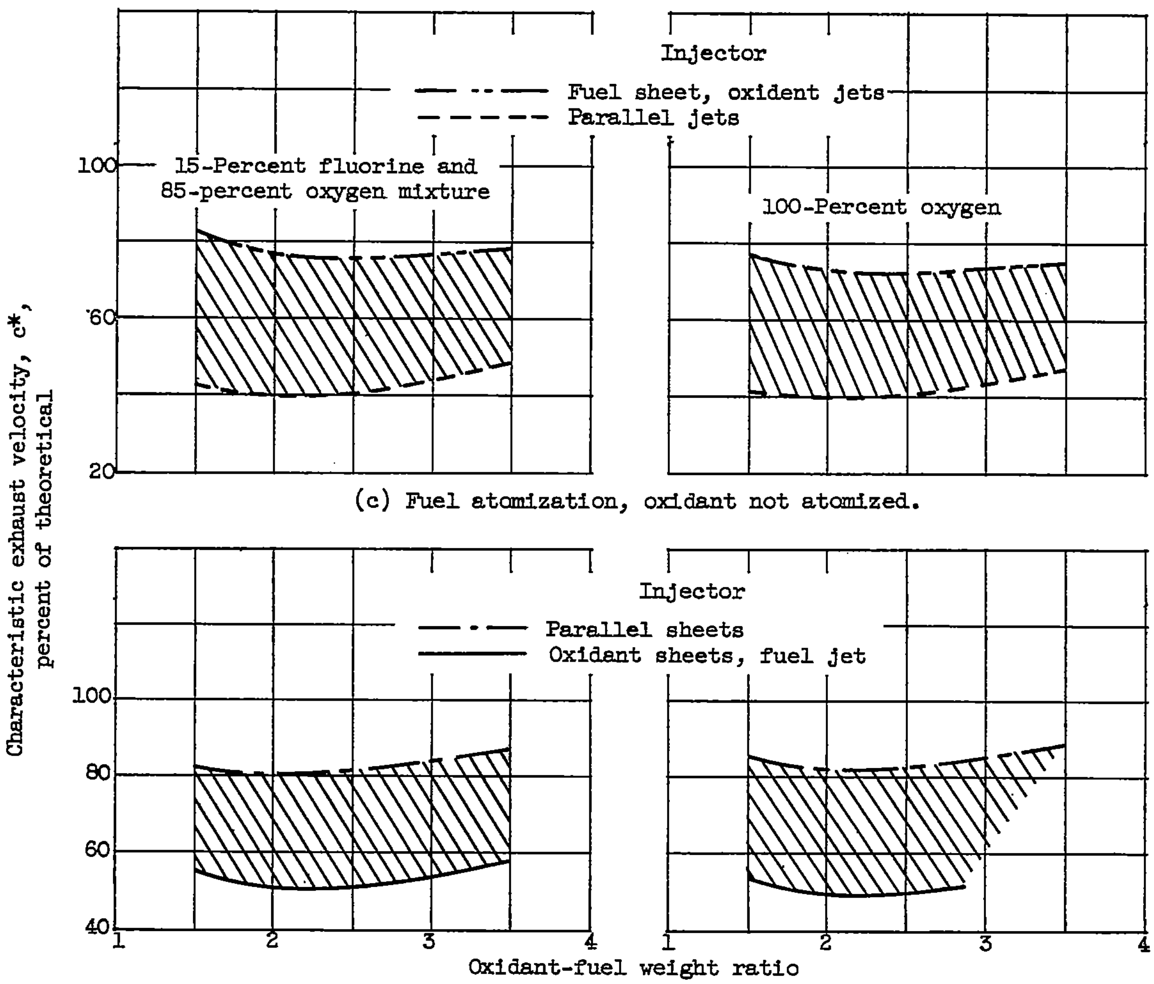

(c) Fuel atomization, oxidant not atomized.

(d) Fuel atomization, oxidant atomized.

Figure 8. - Continued. Performance gain for various injection processes from a comparison of injector performance for both 15-percent fluorine and 85-percent oxygen mixture and 100-percent oxygen with heptane.

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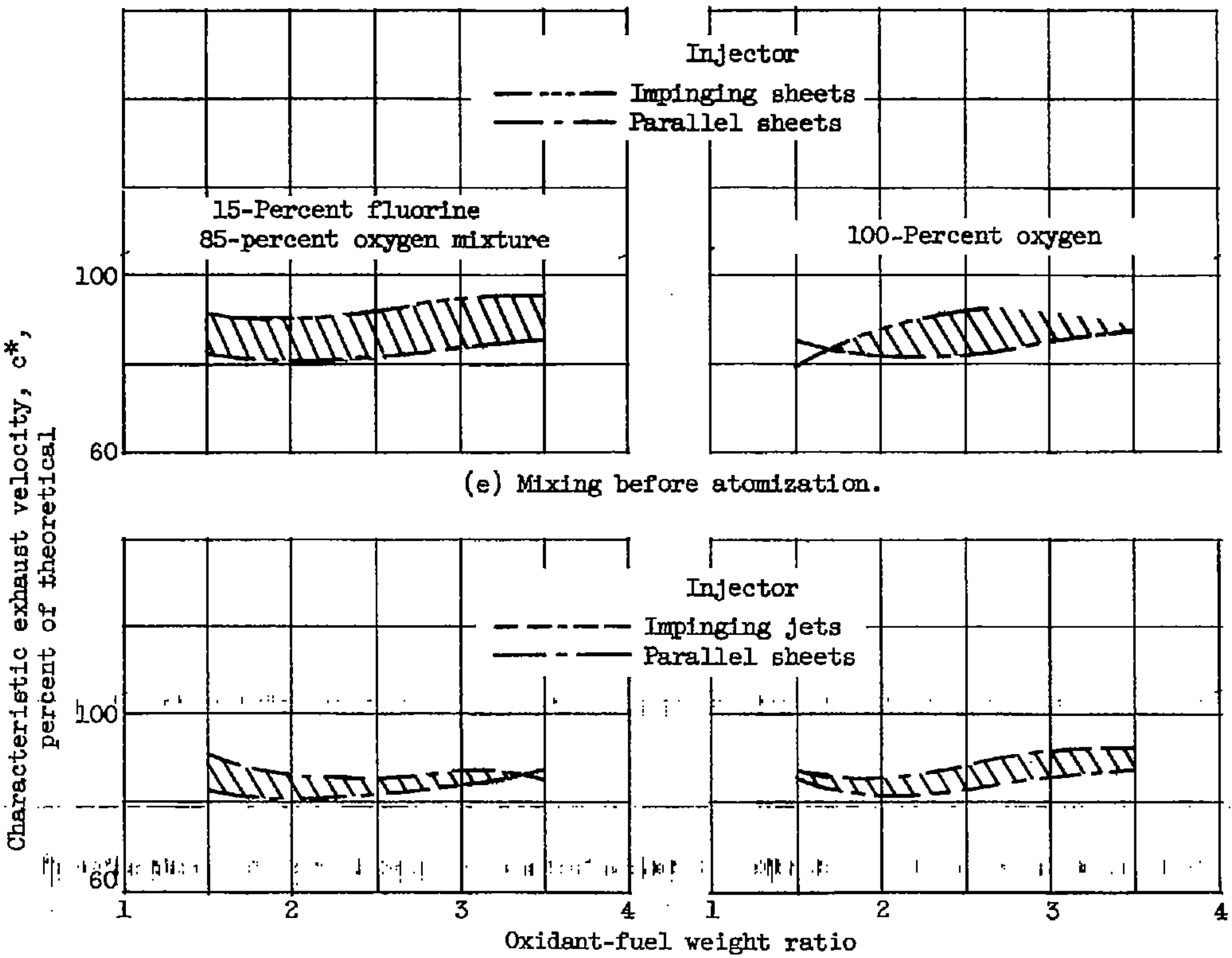

(e) Mixing before atomization.

(f) Mixing after atomization.

Figure 8. - Concluded. Performance gain for various injection processes from a comparison of injector performance for both 15-percent fluorine and 85-percent oxygen mixture and 100-percent oxygen with heptane.

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